The Evidence for a Pentaquark Signal and Kinematic Reflections

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(Dated: February 1, 2008)

Several recent experiments have reported evidence for a narrow baryon resonance with positive strangeness (Θ^+) at a mass of 1.54 GeV/c^2. Baryons with $S = +1$ cannot be conventional qqq states and the reports have thus generated much theoretical speculation about the nature of possible $S = +1$ baryons, including a 5-quark, or pentaquark, interpretation. We show that narrow enhancements in the K^+n effective mass spectrum can be generated as kinematic reflections resulting from the decay of mesons, such as the $f_2(1275)$, the $a_2(1320)$ and the $\rho_3(1690)$.

PACS numbers: 11.80.Cr, 13.60.Le, 13.60Rj
Keywords: meson resonances, baryon resonances

Several experiments have recently claimed evidence for a so-called Θ^+, a positive strangeness baryon resonance with a very narrow width [1, 2, 3, 4]. Baryons with $S = +1$ cannot be simple qqq states and indeed the failure to find $S = +1$ baryons in the 1960's (they were then called Z^*'s) gave credence to the original quark model. QCD can accommodate $S = +1$ baryons as more complicated structures such a five-quark states known as *pentaquarks*. Indeed, the recent experimental claims have generated much theoretical interest and speculation about the nature of the Θ^+ and the possibility of searching for other states that may be members of a larger multiplet.

Guided by the principle of parsimony and by the fact that earlier searches did not uncover $S = +1$ baryon resonances, we examine more conventional mechanisms that could account for narrow structures in meson-baryon effective mass combinations with $S = +1$. That is the focus of this paper. We examine the effect of the constrained kinematics characterizing the experiments reporting the Θ^+ and the possibility that details of the decay angular distribution of known meson resonances could account for enhancements in effective mass, *e.g.* K^+n, distributions.

It is interesting to note that in an earlier search [5] for a Z^* in the reaction $\pi^-p \to K^-Z^*$ at incident π^- momenta of 6 and 8 GeV/c found enhancements in the missing mass recoiling off of the K^- near 1.5 and 1.9 GeV/c^2. The authors explained the enhancements as being kinematic reflections of the $f_2(1275)$, the $a_2(1320)$ and the $\rho_3(1690)$. It was also observed that the peak position of the enhancements changed with changing beam momentum supporting their interpretation of the enhancements.

Three of the experiments [1, 2, 3] claiming the Θ^+ used incident photons scattering off of p [3], d [2] and ^{12}C [1] targets. Two of these experiments produced bremsstrahlung photons beams with electron energies of 2.47 and 3.1 GeV [2] and 2.8 GeV [3] (the photon spectrum extends up to 95% of the electron energy) and the other used Compton backscattered photon beams starting with electron energies above 1.5 GeV and less than 8 GeV. One of the experiments [4] used a low energy K^+ beam scattered off of a Xe target.

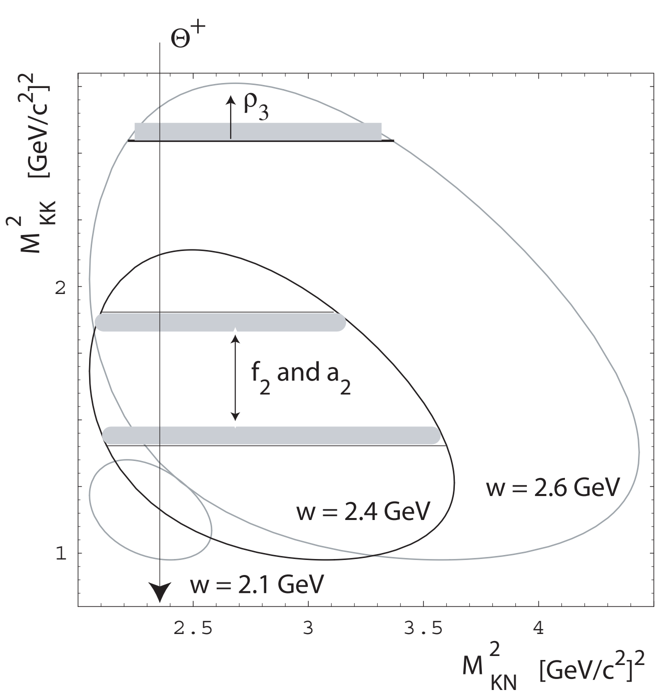

FIG. 1: Boundaries of the m^2_{KK} versus m^2_{KN} Dalitz plot for three different values of w, the energy available to the $K\bar{K}N$ system, 2.1, 2.4 and 2.6 GeV. For the data of ref. [2], the observed distribution in w rises from 2.1 GeV, peaks at 2.4 and falls to zero near 2.6 GeV. Horizontal lines denote the region spanned by the f_2 and a_2 mesons defined by their half-widths and the region of the ρ_3 starting with its central mass less its half-width. The vertical line denotes the square of the Θ mass.

Figure 1 shows the kinematic boundaries of the m^2_{KK}

Reaction	Beam energy GeV	Cross Section μb	Ref
γp $\rightarrow$ f_2p	2.3-2.6	1.3 ± 0.37	[6]
γp $\rightarrow$ f_2p	2.6-3.25	0.39 ± 0.13	[6]
γp $\rightarrow$ f_2p	3.25-4.0	0.19 ± 0.06	[6]
γp $\rightarrow$ f_2p	4.0-6.3	0.1 ± 0.1	[6]
γp $\rightarrow$ a_2^+n	4.2 ± 0.5	1.14 ± 0.43	[7]
γp $\rightarrow$ a_2^+n	5.25 ± 0.55	0.85 ± 0.43	[7]
γp $\rightarrow$ a_2^+n	7.5 ± 0.7	0.43 ± 0.43	[7]
γp $\rightarrow$ K^+K^-p	2.8	1.0 ± 0.1	[8]
γp $\rightarrow$ K^+K^-p	4.7	0.7 ± 0.1	[8]

TABLE I: Photoproduction cross sections for the $f_2(1275)$ and $a_2(1320)$ resonances and the K^+K^- final state.

versus m^2_{KN} Dalitz plot for three different values of w, the energy available to the $K\bar{K}N$ system, 2.1, 2.4 and 2.6 GeV. The observed value of w is determined by the beam momentum, the Fermi momentum of the target and the cuts used to define the data sample. For the data of ref. [2], the observed distribution in w rises from 2.1 GeV, peaks at 2.4 and falls to zero near 2.6 GeV. The other experiments reporting the Θ^+ have similar ranges of energies available to the $K\bar{K}N$ system. Horizontal lines denote the region spanned by the f_2 and a_2 mesons defined by their half-widths and the region of the ρ_3 starting with its central mass less its half-width. The vertical line denotes the square of the Θ mass. As the energetically allowed area of the Dalitz plot grows from smallest to largest the intersection of the f_2, then a_2 and finally ρ_3 bands with the boundary cluster about a value of m_{KN} near the Θ mass.

Because of the constrained kinematics, the projections of the Dalitz plot onto the m_{KN} axis can be strongly influenced by the decays of $K\bar{K}$ resonances. Consider the transformation from the $K\bar{K}N$ system in its center-of-mass to the helicity frame of the $K\bar{K}$ system (center of mass of the $K\bar{K}$ with the $K\bar{K}$ line-of-flight defining the z-axis). In this frame the decay angular distribution of the $K\bar{K}$ is described by $|Y^M_L(\theta,\phi)|^2$ where $L=1$ for the $\phi(1020)$, $L=2$ for the $f_2(1275)$ and the $a_2(1320)$ and $L=3$ for the $\rho_3(1690)$. Several of these mesons are known to have photoproduction cross sections approaching the total cross section for K^+K^- (see Table I). All of them have well established decays into K^+K^- with branching fractions of several percent making plausible the argument that production and subsequent decay of these mesons can produce contributions to observed distributions of the same size as the observed Θ^+. As the spin (L) of the mesons increases, the greater the alignment of the decay products parallel to or anti-parallel to the line of flight of the meson – or alternatively – parallel or anti-parallel to the nucleon (N). In fact, the distribution in the decay angles correlates with the KN mass distribution.

Experiments (*e.g.* ref. [2]) have removed events with

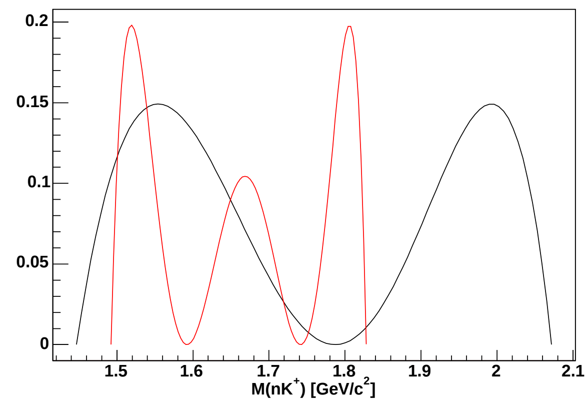

FIG. 2: The m_{KN} mass distribution for a fixed m_{KKN} mass of 2.6 GeV/c^2. The two-peaked curve assumes $m_{KK}=m(a_2)$ with $|Y_2^{\pm1}|^2$ and and the three-peaked curve assumes $m_{KK}=m(\rho_3)-\Gamma_\rho/2$ with $|Y_3^{\pm1}|^2$ for the decay angular distribution.

$m_{K\bar{K}} < 1.07$ GeV/c^2 to avoid the strongly-produced $\phi(1020)$ but not the higher mass and higher spin resonances.

Figure 2 shows the m_{KN} distribution obtained from simply assuming production of an $a_2(1320)$ with no-helicity-flip *i.e* with a decay angular distribution described by $|Y_2^{\pm1}(\theta,\phi)|^2$ (two-peaked curve) and the $\rho_3(1690)$ described by $|Y_3^{\pm1}(\theta,\phi)|^2$ (three-peaked curve). For the plot of this figure the mass of the $K\bar{K}N$ system was assumed to be 2.6 GeV/c^2. The plot illustrates how sharp peaks can be generated and how the m_{KN} distribution is reflected in the form of the decay angular distribution.

The enhancements shown in Figure 2 will be broadened after integrating over $K\bar{K}N$ energy – variations due to the spread in beam momentum and Fermi motion – and the K^+K^- mass. To study these broadening effects, we focus on the data of ref. [2] for $\gamma d \rightarrow K^+K^-np$. We assume that the K^+K^- results from a coherent production of resonances $X = a_2, f_2, \rho_3$. In addition, as in ref. [2], we assume that the reaction takes place off of the neutron with the proton in the deuteron acting as a spectator, $\gamma n \rightarrow Xn \rightarrow K^+K^-n$. At the energies of ref. [2], ranging from $E_\gamma = 1.51$ GeV to $E_\gamma = 2.96$ GeV, meson production can be effectively described by t-channel, Regge exchange amplitudes,

$$A(\gamma n \rightarrow K^+K^-n) = P(\gamma n \rightarrow Xn)D(X \rightarrow K^+K^-) \quad (1)$$

where

$$P(\gamma n \rightarrow K^+K^-n) = s^{\alpha(t)}R(t)|t-t_{\min}|^{n/2}, \quad (2)$$

and

$$D(X \rightarrow K^+K^-) = \frac{k^L Y_{LM}(\Omega_H)}{(m^2_{KK}-m^2_X)+im_X\Gamma(m_{KK})}. \quad (3)$$

a_2 photoproduction has been studied previously [7, 9, 10] and can be well described by a π exchange corresponding to $\alpha(t) = 0.9(t - m_\pi^2)$ GeV^{-2} and $R(t) = \exp(bt)$ with $b = 10 - 30$ GeV^{-2} with $b = 3$ GeV^{-2} for low-t ($|t| < 0.2$ GeV^2) and high-t, *respectively.* For simplicity we assume the same form of energy and momentum transfer dependence for production of the other resonances. The helicity structure of the production amplitude is given by last factor in Eq. (2), with n equal to the net helicity flip. For nucleon-flip pion exchange, assuming Regge factorization, we have $n = 1+|1-M|$ where M is the helicity of the resonance. In the decay amplitude of Eq. 3), L stands for the spin of the resonance, k is the resonance breakup momentum, $k = \sqrt{m_X^2/4 - m_K^2}$, Ω_H represents the helicity angles of the K^+ and m_X and $\Gamma(m)$ are resonance's mass and energy-dependent width, respectively. To compare with the data of ref. [2] we convolve the theoretical cross section calculated from amplitudes given above with the bremsstrahlung photon spectrum and the neutron Fermi momentum distribution in a deuteron. The m_{KN} spectrum is then obtained by integrating over all remaining kinematic variables subject to the requirement that $m_{KK} > 1.07$ GeV and is shown in Figure 3. The theoretical spectrum depends on (complex) resonance strengths, in addition to a coherent S and P wave production. These parameters are obtained from fitting the m_{KN} distribution from ref. [2]. The low-angular momentum waves are expected due to residual $K\bar{K}$ interactions which, for example, are responsible for the $f_0(980)$ meson. At higher K^+K^- mass one expects contributions from the $f_0(1370)$ and higher scalar resonances. Finally, the presence of the P-wave above the $\phi(1020)$ has been established in other photoproduction experiments, [11, 12, 13]. The theoretical K^+K^- distribution fixed by the m_{KN} data is then compared with the experimental K^+K^- distribution from ref. [2] and is shwon in Figure 4. The agreement is very good considering that the P-wave is constrained outside the $\phi(1020)$ region.

It is clear that a enhancement at m_{KN} close to the purported Θ^+ mass, due to peaks in the K^+K^- angular distribution, remains after taking into account the cross section and s- distributions.

We have shown that kinematic reflections due to meson resonances could well account for the enhancement observed in the K^+n effective mass distribution at the mass of the purported Θ^+. Further experimental studies will be required with higher statistics, varying the incident beam momentum and establishing the spin and parity before claiming solid evidence for a $S = +1$ baryon resonance.

The authors acknowledge useful discussions with Curtis Meyer and Elton Smith. This work was supported in part by the National Science Foundation and the U. S. Department of Energy.

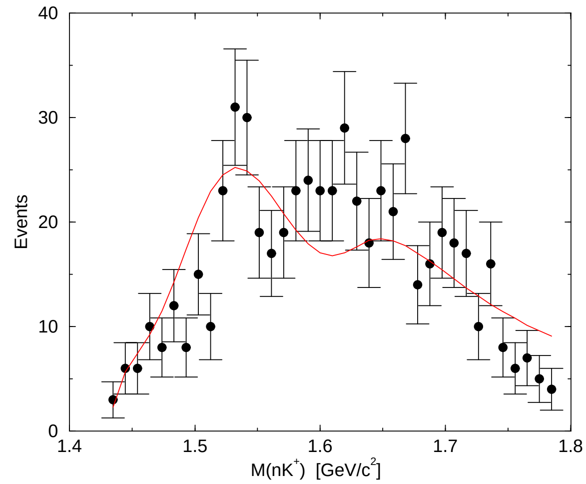

FIG. 3: The calculated (solid line) m_{KN} distribution, as described in the text, compared with the data from [2]

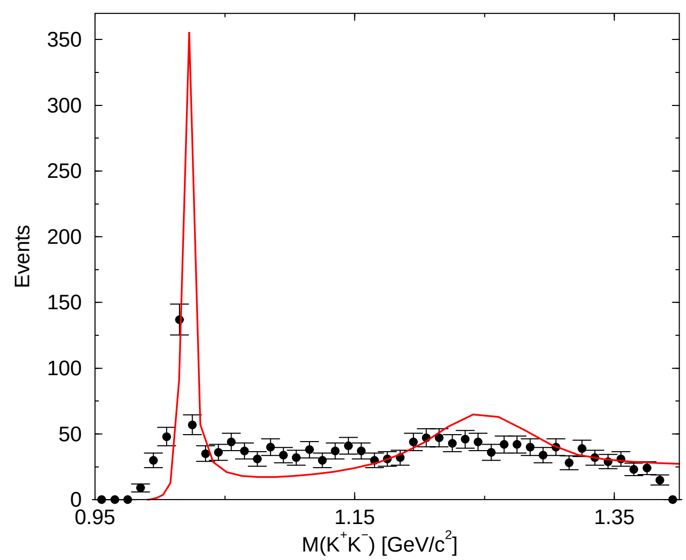

FIG. 4: The calculated (solid line) m_{KK} distribution,, as described in the text, compared with the data from [2]

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